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Reaction mechanism in multi-nucleon transfer studies

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Abstract : The transfer probabilities to low-lying states of residual nuclei excited in one and two proton transfer reactions have been extracted from the study of angular distributions of cross sections in the nuclear reaction ^{88}Sr (^{12}C, X) at an incident energy of 87.5 MeV and show an exponential fall off at large distances The measured slope for two proton transfer is less than the slope observed for one proton transfer An enhancement of proton pair transfer probability for the $0^+ \to 0^+$ ground state transition over and above the predictions based on the model of independent sequential transfer of two protons is observed

Keywords : Multi-nucleon transfer reactions, angular distribution

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1. Introduction

In collisions between heavy nuclei, simultaneous transfer of several nucleons becomes possible leading to dissipation of energy and angular momentum. The present study aims to understand the mechanism of multi-nucleon transfer in heavy ion induced nuclear reactions.

2. Experimental details and results

The experimental details and the analysis of one proton stripping reaction ^{88}Sr (^{12}C, ^{11}B) date are reported in these Proceedings [1]. In the two proton stripping reaction ^{88}Sr (^{12}C, ^{10}Be) transitions to ground state (0^+) and low lying excited states in ^{90}Zr have been identified (Figure 1) by putting appropriate gate on ^{10}Be. The nature of spectrum is similar to the data of Tung *et al* [2]. Absolute differential cross sections to the transitions observed have been obtained.

3. Analysis and discussion

The transfer probability P_{tr} is defined as a function of d_o corresponding to a *c.m.* angle θ by the relations : $P_{tr}(d_o) = [d\sigma / d\Omega]_{tr}(d_o) \times \{[d\sigma / d\Omega]_{el}(d_o)\ [F_L(Q)]\}^{-1}$; $d_o = n(1 + 1/\sin\sigma/2) \times \{A_1^{1/3} + A_1^{1/3}\}^{-1}$ and $n = 2xZ_1 \times Z_2xe^2 / E_{cm} F_L(Q)$ is the dynamical

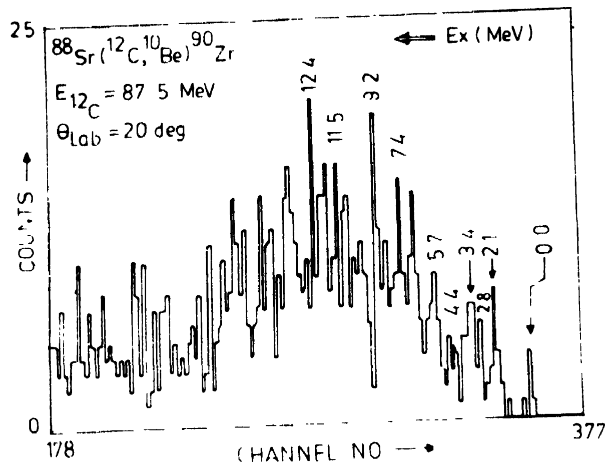

Figure 1. Energy spectrum of ^{10}Be in ^{88}Sr (^{12}C, ^{10}Be) ^{90}Zr at E_{inc} = 87.5 MeV, $\theta_{LAB} = 20^0$.

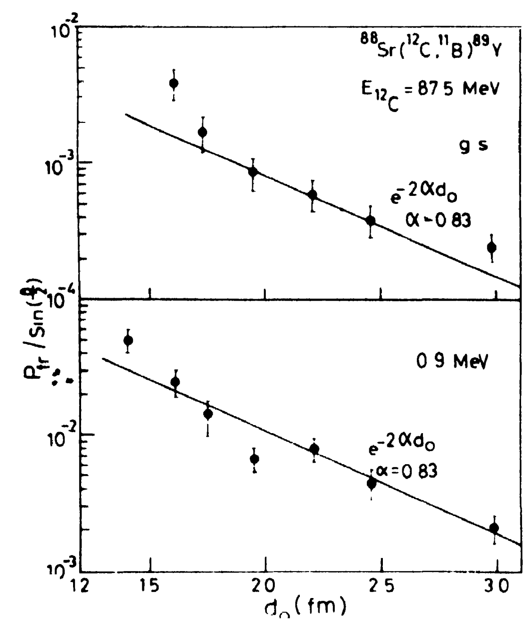

Figure 2. Transfer probability $P_{1N}(d_o)$. See text for details.

matching factor which measures the deviations from the optimum conditions due to transfer of charge, mass *etc.* Calculations based on the semi-classical model [3] for extracting F_L (Q) have been performed.

The angular distribution data for transitions to the ground state and 0.89 MeV state in ^{89}Y and the ground state in ^{90}Zr and the corresponding data for the elastic channel are used to obtain the transfer probabilities P_{1N} and P_{2N} for the one proton and two proton transfer reactions respectively. The transfer probability *i.e.* $P_{1N}/\sin(\theta/2)$ for both the transitions in ^{89}Y (Figure 2) show an exponential fall off ($e^{-2\alpha d_o}$) for $d_o > 1.4\,fm$ with a decay constant $(2\alpha d_o) = 1.66\,fm^{-1}$. In the semiclassical approach the exponential decay constant is related to the reduced mass and the effective binding energy of the transferred nucleon [3]. The exponential dependence of $P_{2N}/\sin(\theta/2)$ at large distance d_o is also observed in the two proton transfer study for transitions to the *g.s.* (0^+) in ^{90}Zr with a decay constant = $1.46\,fm^{-1}$ (Figure 3).

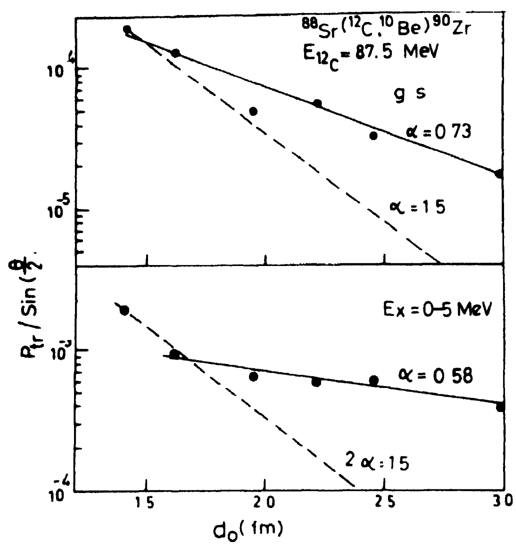

Figure 3. Transfer probability $P_{2N}(d_o)$. The slope of the dashed line corresponds to the binding energy of two protons in ^{12}C. See text for details.

The mechanism for transfer of two protons may involve (a) direct one step transfer of a pair of protons and (b) sequential transfer of two protons, – essentially a two step process. Under the complete independent particle situation which implies that each transfer step has the same probability, the probability of sequential transfer of two protons is the square of the one proton transfer probability *i.e.* $[P_{1N}]^2$. As long as one can talk of filling the protons in the same single particle orbital a comparison of the two quantities namely P_{2N} and $[P_{1N}]^2$ obtained in the present experiment define an enhancement factor

$$EF = [P_{2N}(d_o)]/[P_{1N}(d_o)]^2$$

The choice of appropriate single particle unit is very necessary for an assessment of the enhancement [3].

The ground state of ^{89}Y is described as due to filling of proton in $2p_{1/2}$ *s.p.* orbit [4]. Under such an assumption, the probability P_{1N} of transfer of proton to single particle state

$2p_{1/2}$ in ^{89}Y is taken as a single particle (*sp*) unit and has a value of $P_{1N}(Sp) = 3.0 \times 10^{-4}$ at $d_o = 1.72\,fm$. The choice of d_o is decided from the consideration of onset of nuclear absorption as seen from our elastic scattering measurements [1]. In the two proton transfer between even even nuclei, transition to 0 are to be considered where the pairing interaction is expected to be effective.

In reactions involving heavy ions $A > 16$, the transfer probability is often obtained from the ratio of energy integrated differential cross section and the corresponding elastic cross section as the poor experimental energy resolution does not let one pick up specific transition. In the present case, we have been able to obtain P_{2N} for a *specific transition*, namely the ground state transition populated in the reaction ^{88}Sr (^{12}C, ^{10}Be) ^{90}Zr and has a value of 2.4×10^{-5} at $d_0 = 1.72\,fm$. The ground state of ^{90}Zr is known [2] to consist of 66% of $[(2p_{1/2})^2]$. Thus an enhancement factor of 266 is obtained (Figure 4). The enhancement is even more at larger d_0 and indicates the importance of the direct one step pair transfer of $[\{2p_{1/2}\}^2]$.

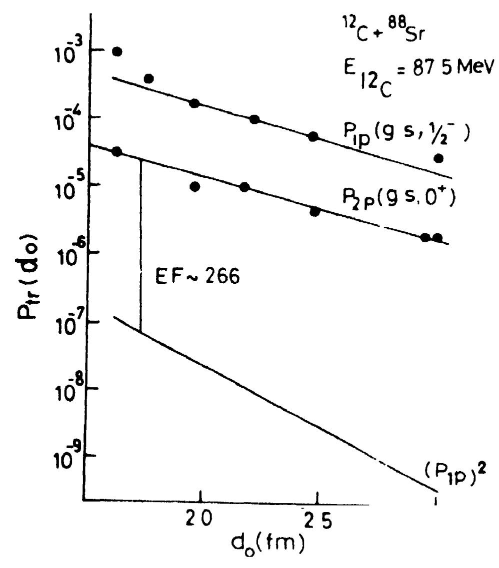

Figure 4. Comparison of one and two $2p_{1/2}$ proton transfer probabilities in ^{88}Sr (^{12}C, X), enhancement factor at $d_o = 1.72\,fm$ is 266. See text for details

We have obtained the two proton transfer probability from the energy integrated (upto 5 MeV excitation) cross section as well and is shown in Figure 3. The value of the slope obtained for the case where specific transition is involved is different for the case when energy integrated cross section is used. Therefore, when discussing the effects due to pairing interaction, it is more appropriate to consider specific transitions.

4. Conclusion

In case of one proton transfer reaction tne experimentally measured slope ($2\alpha = 1.66\,fm^{-1}$) is about the same as that predicted from the binding energy of the transferred proton in ^{12}C.

This probably indicates the validity of simple semi-classical tunneling model even at incident energies above the Coulomb barrier. From the binding energy considerations one expects that the $2p$ transfer probability should fall approximately twice as steeply as the $1P$ transfer, *i.e.* $(2\,\alpha_{2N}) = 2(2\alpha_{1N})$. The measured data yields a slope ($2\alpha = 1.46\,fm^{-1}$) for the two proton transfer reaction which is even less than the slope of one proton transfer reaction ($2\alpha = 1.66\,fm^{-1}$). Similar slope anomaly effect in $2p$ transfer at energies avove the Coulomb barrier has also been reported [5]. Efforts are being made to understand the slope anomaly in terms of localisation of transfer reaction in angular momentum space as suggested in the model of Harney [6].

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